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(71) Applicant: THE REGENTS OF THE UNIVERSITY OF CALIFORNIA [US/US]; 21st floor, 300 Lakeside Drive, Oakland, CA 94612-3550 (US).

(72) Inventors: JUDY, Jack, W.; 2041 Francisco Street #5, Berkeley, CA 94709 (US). MULLER, Richard, S.; 51 Kenyon Avenue, Kensington, CA 94708 (US).

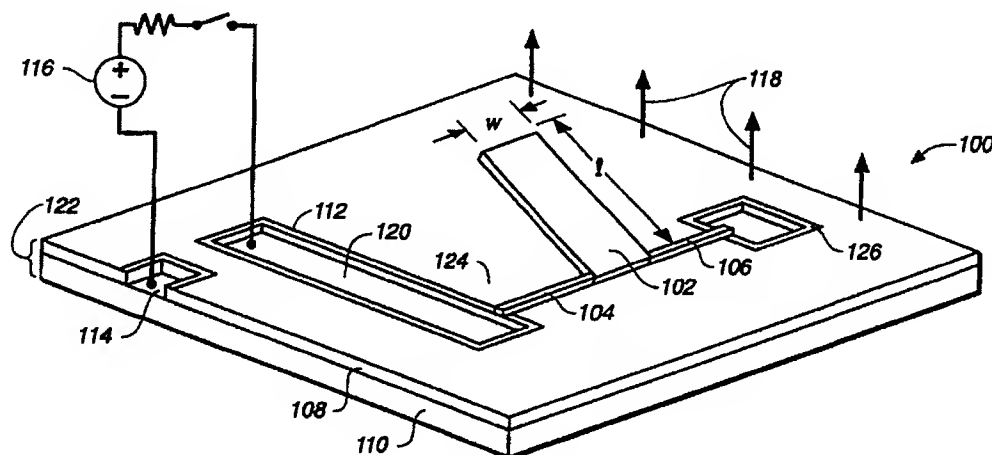
(74) Agent: EGAN, William, J., III; Fish &amp; Richardson P.C., Suite 100, 2200 Sand Hill Road, Menlo Park, CA 94025 (US).

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(54) Title: MAGNETIC MICROACTUATOR



## (57) Abstract

A selectively actuatable microstructure (100) is provided having a base (122), a cantilevered element supported by at least one mechanical attachment (104) attached to the base which permits the element to change its orientation, and at least one layer of magnetically active material placed on one or more regions (104, 106) of a surface of the cantilevered element. A selectively applied magnetic field can apply torque to the cantilevered element and cause it to move. A voltage source (116) causes a Coulombic attractive force for holding the cantilevered element against movement in the presence of an applied magnetic field. A number of the selectively actuatable microstructure may be provided in an array so that each of the microstructure may be individually actuated by the selective switching of the corresponding voltage sources.

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## MAGNETIC MICROACTUATOR

Background

5           The present invention relates generally to micromachined structures, and more particularly to three-dimensional, thin-film, micromachined magnetic microactuators that may be selectively addressed.

          Microelectromechanical systems often integrate  
10 micromechanical and microelectronic devices on the same silicon chip. These systems have many useful applications such as microsensors and microactuators. The accelerometer chips used to trigger air bag inflation in automobiles in the event of a collision are an example  
15 of a microsensor. Microvalves used to control fluidic circuits are examples of microactuators.

          Microstructures can be made by photolithography and etching of deposited thin films to yield desired  
20 shapes. This is called "surface micromachining" because the thin films are deposited on a surface. The films are typically formed through the process of low-pressure chemical vapor deposition (LPCVD).

          Integrated circuit and magnetic recording-head  
25 fabrication technologies can be used to machine microelectrical and micromechanical devices. These devices have mechanical and electrical components that typically require actuation to perform their intended functions. Such actuation can be accomplished by several  
30 methods including electrostatic and magnetic forces.

          Components which create electrostatic forces are relatively easy to manufacture. These forces are large if operated with small gaps between electrodes, but small otherwise. They can be integrated with and controlled by  
35 integrated circuits.

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The electrostatic forces typically used in micromachines are attractive rather than repulsive. Attractive forces may be disadvantageous when it is desired to move a structure away from a surface because  
5 an electrode that overhangs the surface may be required in such a case.

Magnetic forces are advantageous for certain microstructure designs. They have the characteristic of often being very large, especially those created using  
10 ferromagnetic materials. In addition, magnetic forces can be created by external sources, resulting in a substantial saving of space.

There are some disadvantages to using magnetic forces. Components which create magnetic forces are  
15 often difficult to manufacture. Also, manual assembly is usually required rather than a continuous batch process.

An object of the invention is to combine the features of electrostatic forces and magnetic forces within the same microstructure.

20 A further object is the design of a magnetic microactuator that may be batch-processed.

#### Summary of the Invention

A selectively actuatable microstructure is provided having a base, a cantilevered element supported  
25 by at least one mechanical attachment attached to the base which permits the element to change its orientation, and at least one layer of magnetically-active material placed on one or more regions of a surface of the cantilevered element. The cantilevered element, the  
30 mechanical attachment, and the magnetically-active material are microfabricated in one batch process such that a selectively applied magnetic field can apply torque to the cantilevered element and cause it to move.

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A first electrical connection may be made to the cantilevered element, and a second electrical connection may be made to the base region. A voltage source may be electrically connected between the first and second  
5 electrical connections to cause a Coulombic attractive force for holding the cantilevered element against movement in the presence of an applied magnetic field.

A number of the above selectively actuatable microstructures may be provided in an array so that each  
10 of the microstructures may be individually actuated by the selective switching of the corresponding voltage sources.

A selectively actuatable microstructure may also be made with a conducting pattern placed on the base  
15 region surrounding the cantilevered element such that a current can be passed through the conducting pattern to cause a magnetic field that is localized in the region of the cantilever for causing the cantilever to move.

This type of selectively actuatable microstructure  
20 may also be made in an array where only the selectively actuatable microstructures that have current passed through their corresponding conducting patterns are actuated. The conducting pattern for each may be, for example, magnetic coils.

25 The mechanical attachment may be at least one torsional support, a flexing material such as polyimide, or a hinged linkage.

The cantilevered element is highly reflective to direct optical beams for displays or communications.

30 The cantilevered element may be a strongly dispersive element in an acoustic beam such that the cantilevered element is easily detectable in an acoustic field such as a medical ultrasound system. The cantilevered element may also serve as a platform for an

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energy source device such as an ultrasound emitter, an electromagnetic radiation emitter, or an energy sensor.

An advantage of the invention is that high-quality arrays of microactuated structures can be batch-  
5 processed. Another advantage is the absence of interactions between adjacent structures and a very high areal density of structures that can be achieved. The invention can be advantageously used in optical scanners, displays, switches, gratings, microflow systems, sensors,  
10 micromirror systems, and in microphotonic applications such as beam chopping and steering.

Additional advantages of the invention will be set forth in the description that follows, and in part will be obvious from the description, or may be learned by  
15 practice of the invention. The advantages of the invention may be realized and obtained by means of the instrumentalities and combinations particularly pointed out in the claims.

#### Brief Description of the Drawings

20 The accompanying drawings, which are incorporated in and constitute a part of the specification, schematically illustrate the invention and, together with the general description given above and the detailed description given below, serve to explain the principles  
25 of the invention.

Fig. 1 is a schematic view of a magnetic microactuator according to a first embodiment of the invention.

Figs. 2(a)-(d) are schematic views of the magnetic  
30 microactuator of Fig. 1, under the influence of various combinations of a magnetic force and an electrostatic clamping force.

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Fig. 3 is a schematic plan view of a magnetic microactuator according to an embodiment of the invention having a restraining stop.

Fig. 4 is a schematic diagram of the  
5 implementation of an  $N \times M$  system of magnetic microactuators used as an optical switch.

Fig. 5(a) is a schematic plan view of a magnetic microactuator according to a second embodiment of the invention, in the unselected or non-actuated condition.

10 Fig. 5(b) is a schematic plan view of a magnetic microactuator according to a second embodiment of the invention, in the selected or actuated condition.

Fig. 6 is a diagram illustrating a partial number of steps of a microfabrication technique for  
15 manufacturing a magnetic microactuator, these steps showing the process up to the step of etching holes where anchors will be placed.

Fig. 7 is a diagram illustrating a partial number of steps of a microfabrication technique for  
20 manufacturing a magnetic microactuator, these steps showing the process of constructing a magnetic plate.

#### Description of the Preferred Embodiments

The following patents describe various types of microelectromechanical structures as well as fabrication  
25 techniques for their manufacture: U.S. Patent 4,674,319 entitled "Integrated Circuit Sensor"; U.S. Patent 4,740,410 entitled "Micromechanical Elements and Methods for Their Fabrication"; and U.S. Patent 5,252,881  
entitled "IC-Processed Micromotors and Methods for their  
30 Fabrication". These patents are assigned to the assignee of the subject application and are hereby incorporated by reference in their entirety.

Referring now to Fig. 1, a magnetic microactuator  
100 is shown having a magnetic plate 102 fabricated on a

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base 122. Magnetic plate 102 is generally a cantilevered element attached to base 122 by a mechanical attachment which permits the element to change its orientation.

Base 122 is fabricated by a deposition process  
5 such as those used in optical-resist technology. Base 122 is usually composed of an insulating layer 108 on top of a lower electrode layer 110. A hole is made through insulating layer 108 to allow a lower contact 114 to electrically connect lower electrode layer 110 with a  
10 clamping voltage supplied by a voltage source 116. An upper contact 112 is formed on top of insulating layer 108 to electrically connect the clamping voltage with the clamping system described below.

Magnetic plate 102 may be a rectangular beam, and  
15 it may constitute a single layer of magnetically-active material. Alternatively, magnetic plate 102 may have a layer of magnetically-active material plated onto a nonmagnetic material. More than one region of the magnetic plate may be so plated. The magnetic material  
20 can be one of various combinations of nickel, iron or other elements, and is usually ferromagnetic with a high saturation magnetization. Magnetic plate 102 is commonly about 430x130x15 cubic micrometers (length x width x height), although plates with their largest dimensions  
25 ranging roughly from 10 micrometers to more than a millimeter can be built.

Magnetic plate 102 is mounted to base 122 by mechanical attachments such as torsion beams 104 and 106 in a torsion-beam suspension system. In an alternative  
30 embodiment, only one beam may be used. Moreover, rather than a torsion-beam suspension, hinged linkages or folding mountings may be used. Flexible materials such as polyimide may also be used as a mechanical attachment.

Mechanical movement in this embodiment is  
35 performed by magnetic plate 102 rotating about torsion



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beams 104 and 106. The torsion beams 104 and 106 constrain the rotation of the magnetic film 102 to a single axis. Torsion beams 104 and 106 are secured against rotation by anchors 120 and 126. They are  
5 generally conductive and can be phosphorus-doped LPCVD polysilicon. They may be about  $400 \times 2.2 \times 2.2$  cubic micrometers (length x width x height). Beams may be used with length dimensions from about 10 micrometers to about a millimeter and cross-sectional dimensions from  
10 approximately 1.0 micrometer by 0.1 micrometers to 100.0 micrometers by 10.0 micrometers.

When a magnetic field 118 is applied, the resulting torque rotates magnetic plate 102 about torsion beams 104 and 106. Rotations of more than  $90^\circ$  can be  
15 achieved. Magnetic field 118 may often be, for example, several kiloamperes per meter. The torque caused by magnetic field 118 can be greater than 3.0 nanonewton-meters and is generally in the range of about 1 nanonewton-meter to about 100 nanonewton-meters.

20 The torque strains torsion beams 104 and 106. The final position of magnetic plate 102 is established when there is equilibrium between the restoring torque from strained torsion beams 104 and 106 and the torque on the system caused by magnetic field 118 on magnetic plate  
25 102.

An electrostatic clamping system is implemented on base 122 to restrain magnetic plate 102 from rotation. The clamping system includes clamping voltage source 116, upper contact 112 for forming a first connection between  
30 magnetic plate 102 and voltage source 116, lower electrode layer 110, lower contact 114 for forming a second connection between base 122 and voltage source 116, and insulating layer 108. In use, an electrostatic clamping field applies a Coulombic force by placing  
35 clamping voltage source 116 across upper contact 112 and

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lower contact 114. A circuit is formed from lower electrode layer 110, clamping voltage source 116, upper contact 112, torsion beams 104 and 106, and magnetic plate 102. Magnetic plate 102, acting as an upper  
5 electrode, rotates back onto clamping area 124 to form one plate of a capacitor that couples to lower electrode layer 110.

The field created by clamping voltage source 116 is generally constant over clamping area 124. It is not  
10 necessary to concentrate the field, as the field will usually be strongest in the clamping area due to the close proximity of the magnetic plate to the lower electrode. Fringing fields may occur around the clamped plate, but these usually are not strong and do not affect  
15 the operation of the microactuator. The clamping voltage source 116 is switchable and can be as low as 5 volts or even lower. The clamping voltage source 116 may be generated by external sources such as power supplies or batteries, or by internal sources on the chip.

20 Figs. 2(a)-(d) show the magnetic microactuator at positions according to the presence of an applied magnetic field 118 and the status of a clamping voltage 116. Fig. 2(b) is similar to Fig. 1. Magnetic field 118 acts to rotate magnetic plate 102 so that its equilibrium  
25 position is out of the plane of base 122. Fig. 2(a) shows the situation when magnetic field 118 is removed. Magnetic plate 102 rests on base 122 because torsion beams 104 and 106 hold the plate against rotation in the absence of magnetic field 118.

30 Figs. 2(c) and (d) illustrate the effect of clamping voltage source 116. When such a clamping voltage is activated, magnetic plate 102 is clamped to base 122 by electrostatic attraction. This can occur whether or not a magnetic field 118 is applied (Figs.  
35 2(c) or (d)).

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The user may choose materials, clamping voltage sources, and applied-magnetic fields to adjust the sensitivity of the microactuator for any particular purpose or application.

5 Referring to Fig. 3, if a simple binary on/off operation is desired, the system may be fabricated so that magnetic plate 102 is stable at only one of two positions. In this case, magnetic field 118 is designed to be strong enough to rotate magnetic plate 102 to a  
10 mechanical restraining stop 135, restraining magnetic plate 102 against further rotation.

It should be noted that magnetic plate 102 need not be a rectangular beam. Other structures having magnetic portions can be used which can move by, for  
15 example, sliding or rolling.

A large array of such microstructures may be fabricated on a chip, and each can be selectively actuated by, for example, an electrostatic address arrangement.

20 An application of such an array is an optical switch. In this case, each magnetic plate 102 may act as a mirror; a suitable mirror coating may be deposited on each to enhance reflectivity if desired. Referring to Fig. 4, an N-by-M array of individually-controlled  
25 microstructures is diagrammed. For clarity, only two optical inputs 401 and 403, and two optical outputs 451 and 453 are shown. The inputs and outputs are usually collimated. The N inputs (401, 403, ...) are along one side of the array and the M outputs (451, 453, ...) are  
30 along an adjacent side. The switching elements are the array of microstructures 102. In each element of the array, magnetic plate 102 is oriented at 45° to an incoming optical beam.

If the  $m$ th element along one of the N input beams  
35 is actuated, that beam is reflected into the  $m$ th of the M

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outputs. All but one mirror in a given input line is held down by the clamping electrostatic voltages on the elements. The actuated mirror selects the output for that line.

5 Another application may be an optical display. A large array of structures are addressed individually forming the reflected image. The display rate is related to the rate at which the structures can be addressed. At atmospheric pressure, the structures may be addressable  
10 at rates on the order of a kilohertz. For operation with video systems having higher rate requirements, the structures may be encapsulated in a vacuum enclosure.

A further application is an optical scanner. In this application, light incident on the magnetic plates  
15 102 can be reflected at an angle controlled by the deflection.

Yet a further application is a sensitive probe of magnetic fields. In this application, varying magnetic fields on the surface can provoke a varying response in  
20 the array.

In a further application, an array of magnetic plates may be made highly reflective to direct optical beams for displays or communications.

In another application, an array of cantilevered  
25 elements may be a strongly dispersive element in an acoustic beam such that the cantilevered element is easily detectable in an acoustic field such as a medical ultrasound system. An array of cantilevered elements may also serve as a platform for an energy source device such  
30 as an ultrasound emitter, an electromagnetic radiation emitter, or an energy sensor.

Referring to Figs. 5a and 5b, a second embodiment includes a magnetic plate 102 which is actuated by a conducting pattern such as an encircling coil 302. In  
35 this embodiment, coil 302, which is generally planar and

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driven by a current source 316, generates a field sufficient to rotate magnetic plate 102 out of the plane of base 122. As in the embodiment above, magnetic plate 122 may be attached to base 122 by mechanical attachments  
5 320.

Fig. 6 illustrates a fabrication technique which may be used to construct the magnetic microactuator. Generally, the cantilevered element such as magnetic plate 102, the mechanical attachments such as torsion  
10 beam 104 and 106, and the plating of a magnetically-active material are fabricated in a single batch process.

As shown in Fig. 6(a), a substrate such as a silicon wafer 401 is loaded into a deposition chamber (not shown). The lower electrode 110 may be formed  
15 first either by heavily doping the surface of the silicon wafer or by depositing a conductive layer of a material such as doped polycrystalline silicon. An insulating dielectric layer 403 such as silicon nitride is then deposited. A sacrificial layer 405 is deposited on top  
20 of the dielectric layer 403. Sacrificial layer 405 is, for example, silicon dioxide doped with phosphorus.

As shown in Fig. 6(b), holes are etched through sacrificial layer 405 to insulating layer 403, creating positions for anchors 120. Holes are also etched (not  
25 shown) through both sacrificial layer 405 and insulating layer 403 to provide lower electrical contact 114.

Referring to Fig. 7(a), a conductive layer 407 is then deposited above the sacrificial layer 405. Conductive layer 407 serves as the mechanical material  
30 from which the magnetic plate, torsion beams, and anchor are eventually constructed. This conductive material may be, for example, phosphorus-doped polycrystalline silicon or a heavily-doped silicon substrate. This material is deposited through the holes in sacrificial layer 405 to  
35 form anchors 120 and 126 (shown in Fig. 7(a)). This

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conductive layer may undergo additional processing such as annealing to improve its mechanical properties. After processing, conductive layer 407 is etched to form the mechanical structure.

5        Before the mechanical structure can be used as magnetic plate 102, a magnetic layer must be deposited. An electroplating seed layer 509 is deposited first on the mechanical structure to prepare it for electroplating. Electroplating seed layer 509 may be,  
10 for example, nickel, an alloy of iron-nickel, or an alloy of copper-chromium.

      A photoresist plating mask 511 is formed (Fig. 7(b)). This mask may be, for example, two micrometers thick. A ferromagnetic material is  
15 electroplated through the mask (Fig. 7(c)). The deposited ferromagnetic material may be nickel, iron, cobalt, or an alloy of these and other materials. The ferromagnetic material is electroplated to a thickness many times that of photoresist plating mask 511, causing  
20 the ferromagnetic material to "mushroom" over the edges of the mask. The ferromagnetic layer 513, together with layer 407, forms magnetic plate 102.

      Photoresist plating mask 511 is then removed along with the unplated areas of electroplating seed layer 509  
25 (Fig. 7(d)), these having previously been covered by photoresist plating mask 511. Sacrificial layer 405 is sputter-etched away to release magnetic plate 102, freeing it to rotate (Fig. 7(e)). The etch used may be a concentrated two-minute hydrogen fluorine bath.

30        The present invention has been described in terms of preferred embodiments. The invention, however, is not limited to the embodiments depicted and described. Rather, the scope of the invention is defined by the appended claims.

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What Is Claimed Is:

1. A selectively actuatable microstructure,  
comprising:

a base;

5 a cantilevered element supported by at least one  
mechanical attachment attached to the base which permits  
the element to change its orientation; and  
at least one layer of magnetically-active material  
placed on one or more regions of a surface of the  
10 cantilevered element;

wherein the cantilevered element, the mechanical  
attachment, and the magnetically-active material are  
microfabricated in one batch process,

such that a selectively applied magnetic field can  
15 apply torque to the cantilevered element and cause it to  
move.

2. A selectively actuatable microstructure,  
comprising:

a base;

20 a cantilevered element supported by at least one  
mechanical attachment attached to the base which permits  
the element to change its orientation;

at least one layer of magnetically-active material  
placed on one or more regions of a surface of the

25 cantilevered element;

a first electrical connection made to the  
cantilevered element;

a second electrical connection made to the base  
region; and

30 a voltage source electrically connected between  
the first and second electrical connections;

such that the voltage source causes a Coulombic  
attractive force for holding the cantilevered element

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against movement in the presence of an applied magnetic field.

3. The structure of claim 2 in which the mechanical attachment is at least one torsional support.

5 4. The structure of claim 2 in which the mechanical attachment is a flexing material such as polyimide.

5. The structure of claim 2 in which the mechanical attachment is a hinged linkage.

6. The structure of claim 2 in which the cantilevered  
10 element is highly reflective to direct optical beams for displays or communications.

7. The structure of claim 2 in which the cantilevered element is a strongly dispersive element in an acoustic beam such that the cantilevered element is easily  
15 detectable in an acoustic field such as a medical ultrasound system.

8. The structure of claim 2 in which the cantilevered element serves as a platform for an energy source device such as an ultrasound emitter, an electromagnetic  
20 radiation emitter, or an energy sensor.

9. An array of selectively actuatable microstructures, each of the microstructures comprising:  
a base;  
a cantilevered element coupled to at least one  
25 mechanical attachment attached to the base which permits the element to change its orientation;



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at least one layer of magnetically-active material placed on one or more regions of a surface of the cantilevered element;

a first electrical connection made to the  
5 cantilevered element;

a second electrical connection made to the base region; and

a switchable voltage source electrically connected between the first and second electrical  
10 connections;

such that the voltage source causes a Coulombic attractive force for holding the cantilevered element against movement in the presence of an applied magnetic field;

15 such that each of the microstructures may be individually actuated by the selective switching of the corresponding voltage sources.

10. A selectively actuatable microstructure, comprising:

20 a base;

a cantilevered element coupled to at least one mechanical attachment attached to the base which permits the element to change its orientation;

at least one layer of magnetically-active  
25 material placed on one or more regions of a surface of the cantilevered element;

wherein the cantilevered element, the mechanical attachment, and the at least one layer of magnetically-active material are microfabricated in one batch process;  
30 and

a conducting pattern placed on the base region surrounding the cantilevered element;

such that a current can be passed through the conducting pattern to cause a magnetic field that is

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localized in the region of the cantilevered element for causing the cantilevered element to move.

11. An array of selectively actuatable microstructures, each of the microstructures comprising:

5 a base;

a cantilevered element coupled to at least one torsional support, the torsional support attached to the base;

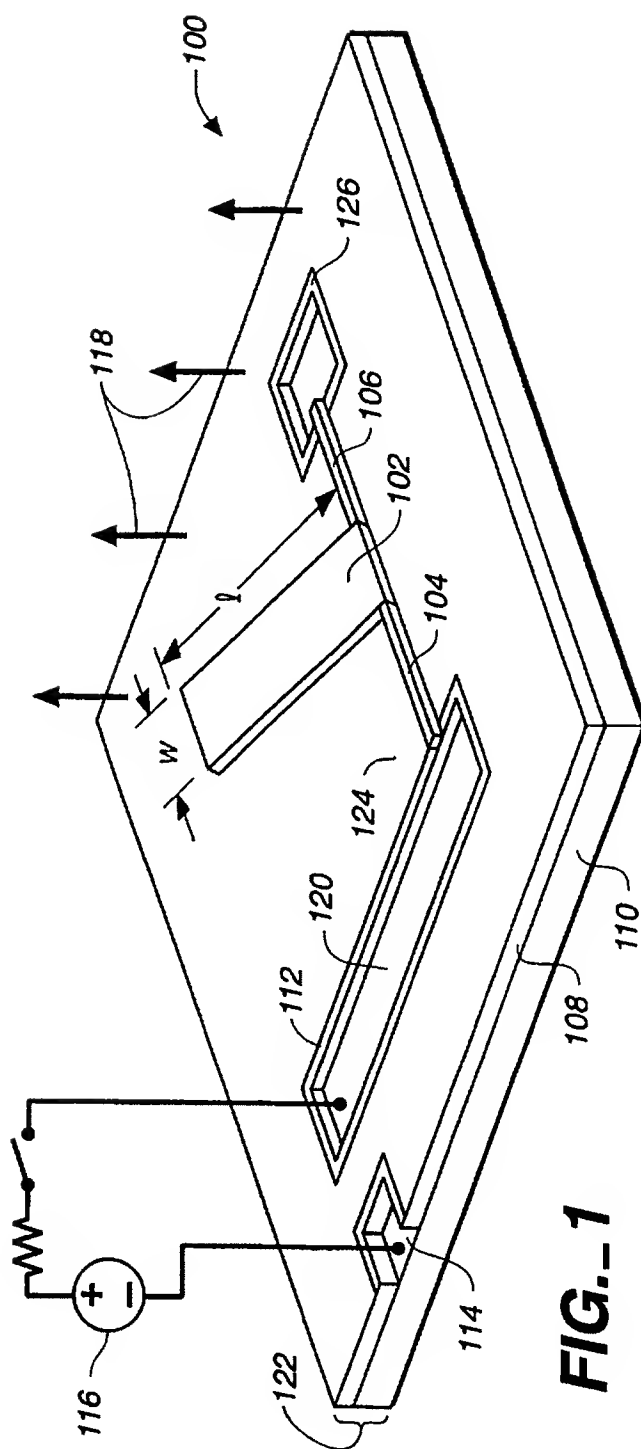
at least one layer of magnetically-active  
10 material placed on one or more regions of a surface of the cantilevered element;

wherein the cantilevered element, the torsional support, and the at least one layer of magnetically-active material are microfabricated in one batch process;

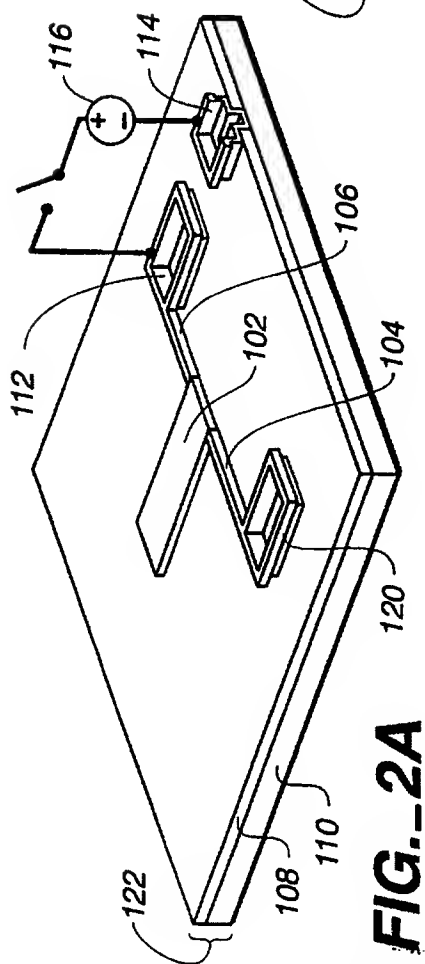
15 and

a conducting pattern placed on the base region surrounding the cantilevered element;

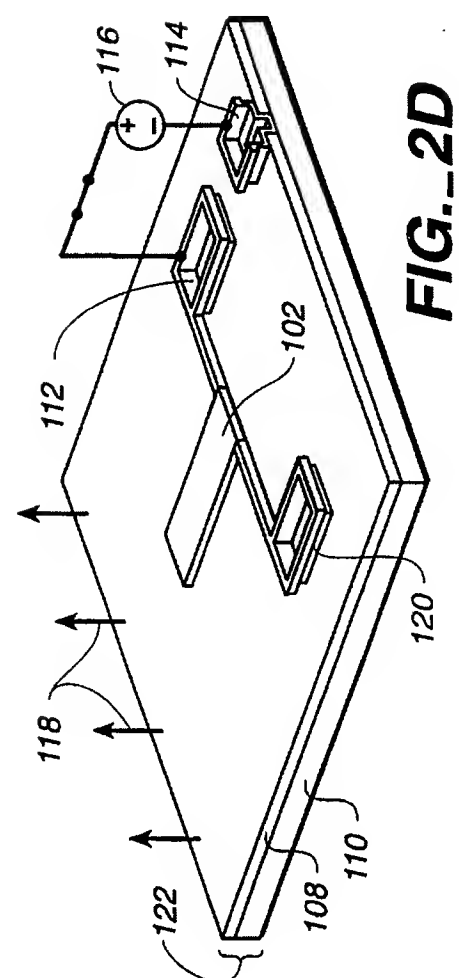
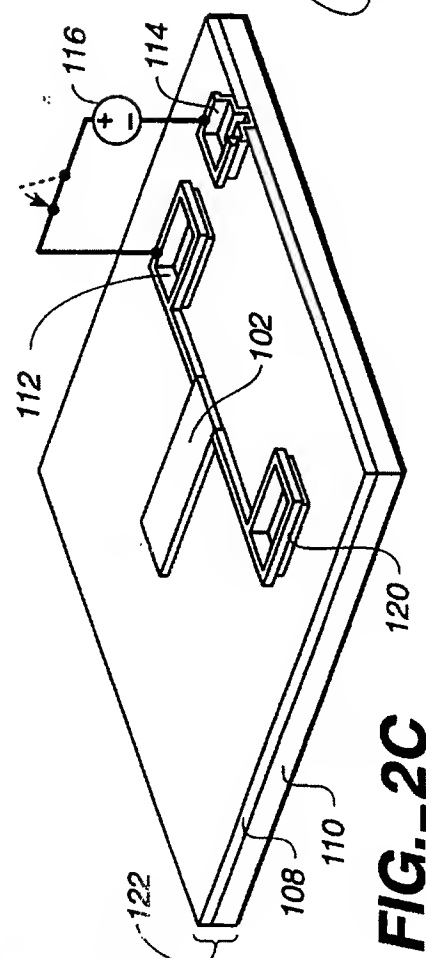
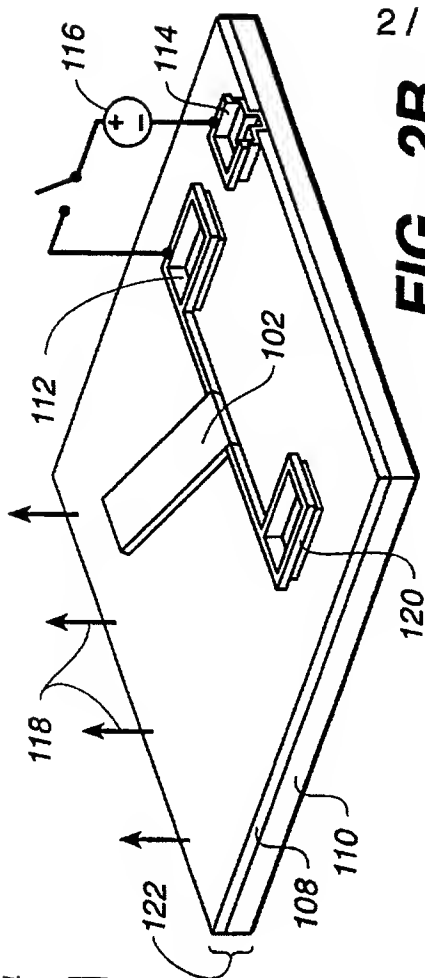
such that a current can be passed through the conducting pattern to cause a magnetic field that is  
20 localized in the region of the cantilevered element for causing the cantilevered element to move such that only the selectively actuatable microstructures that have current passed through a corresponding conducting pattern are actuated.



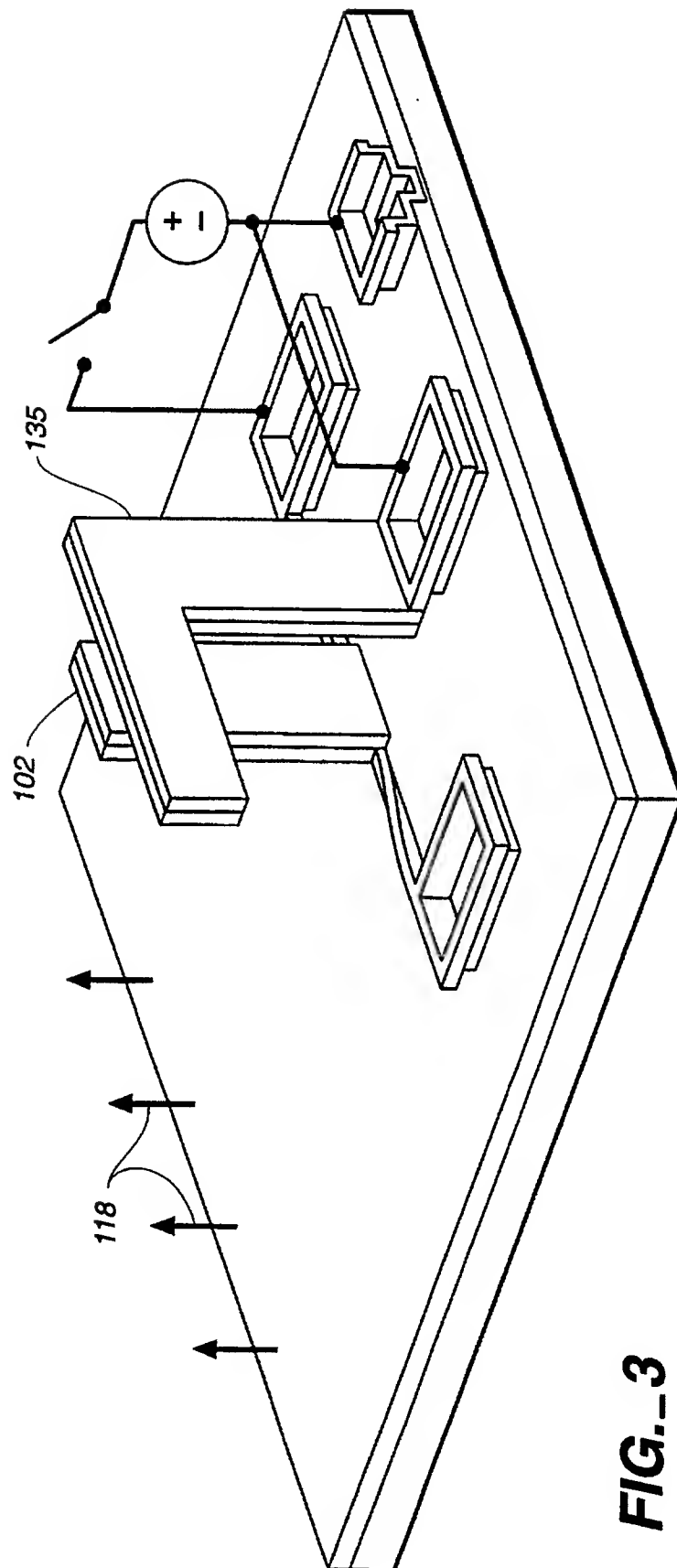
**FIG. 1**



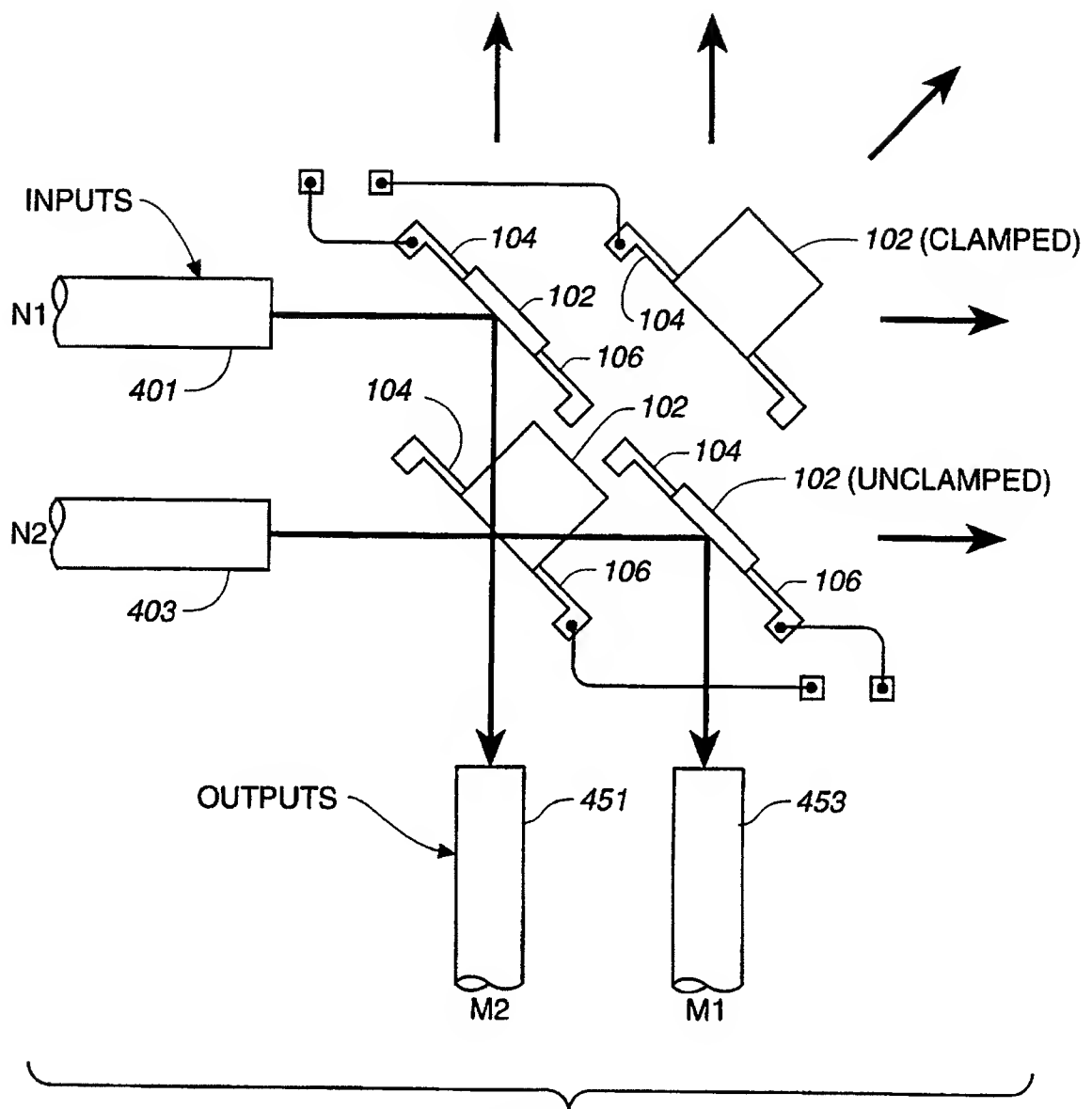
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**FIG. 2B**

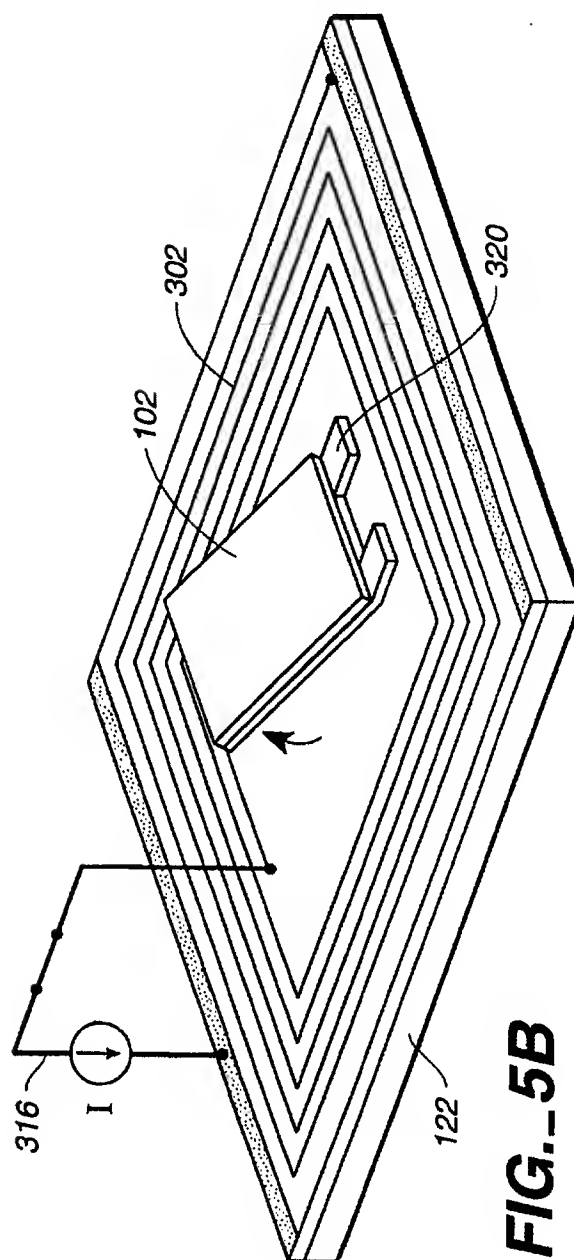
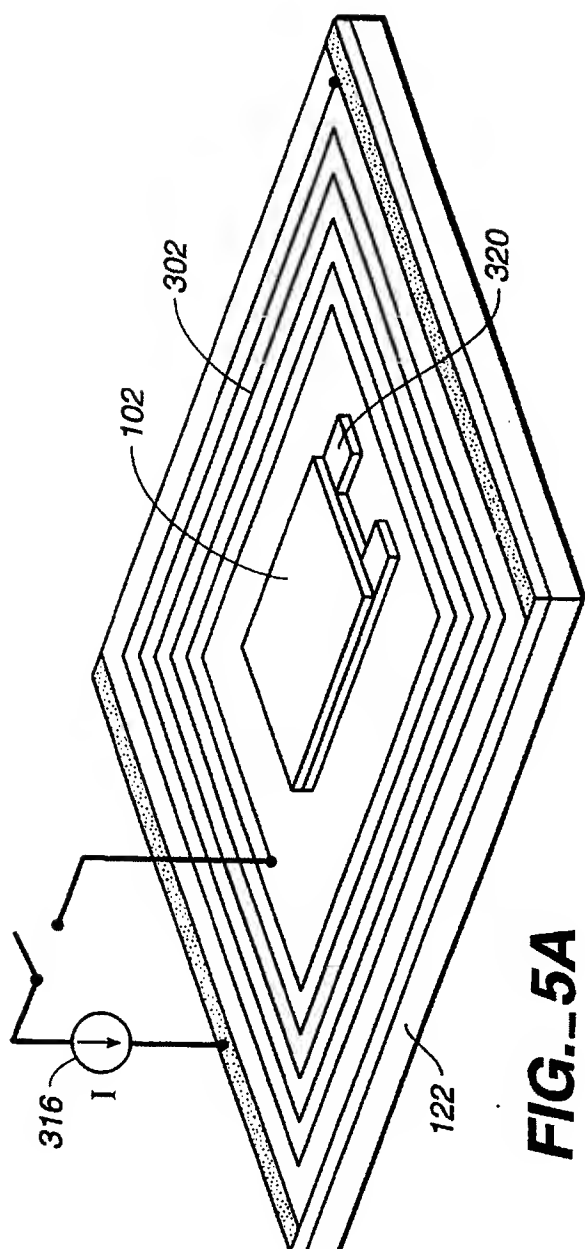


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**FIG. 4**



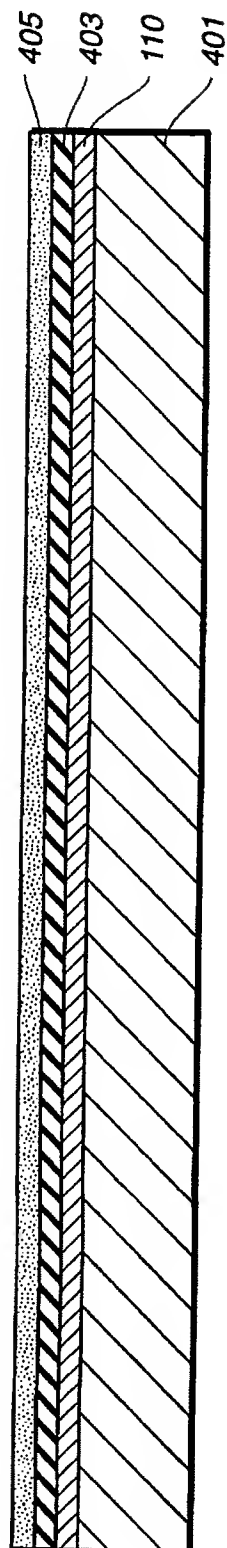


FIG. 6A

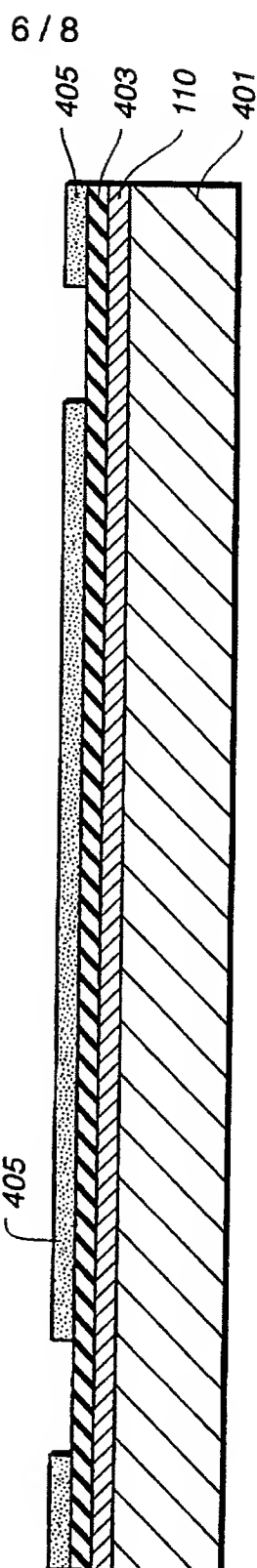


FIG. 6B

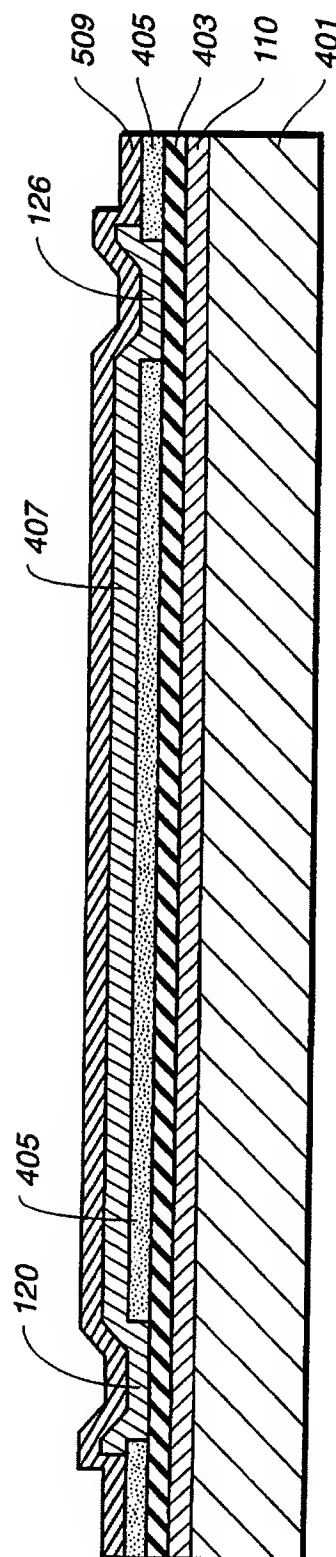


FIG. 7A



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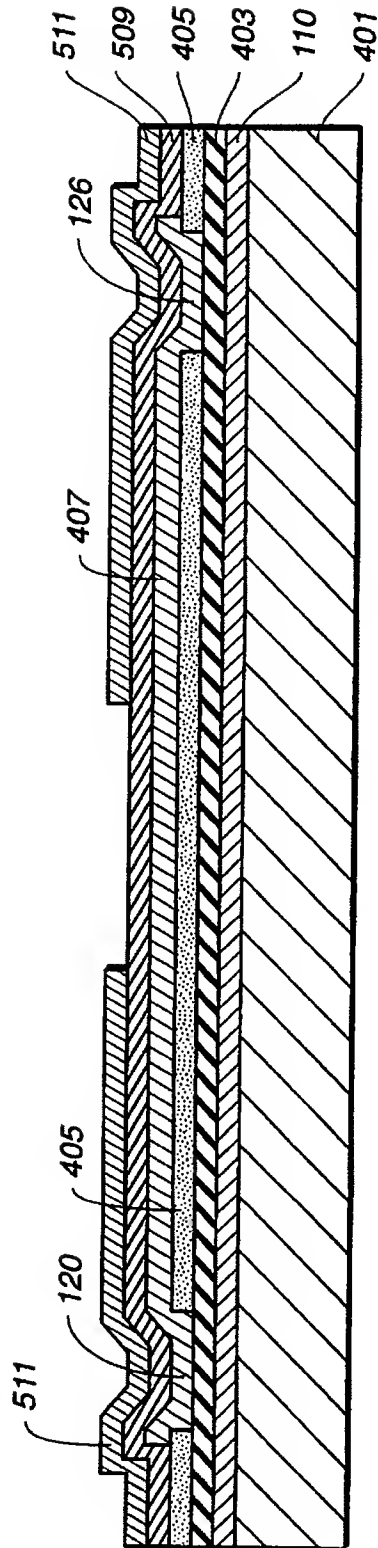


FIG. 7B

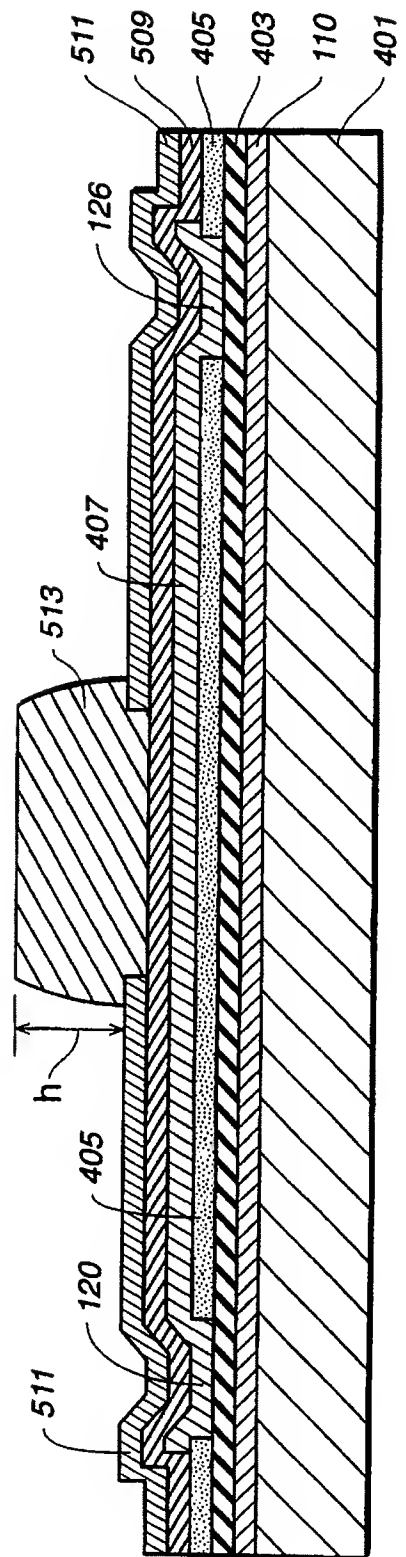


FIG. 7C

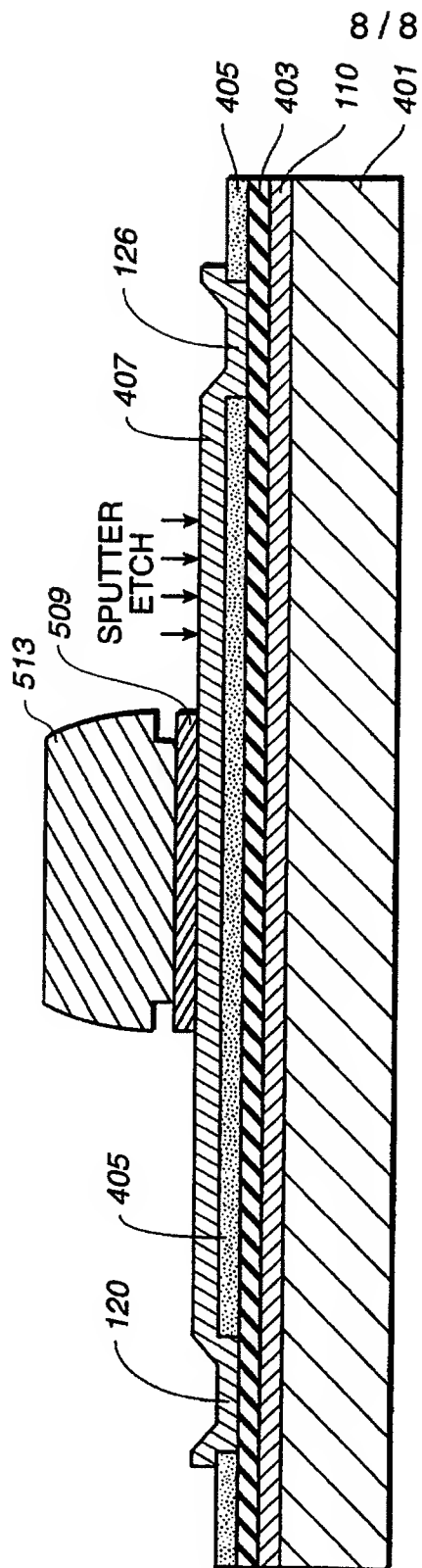


FIG. 7D

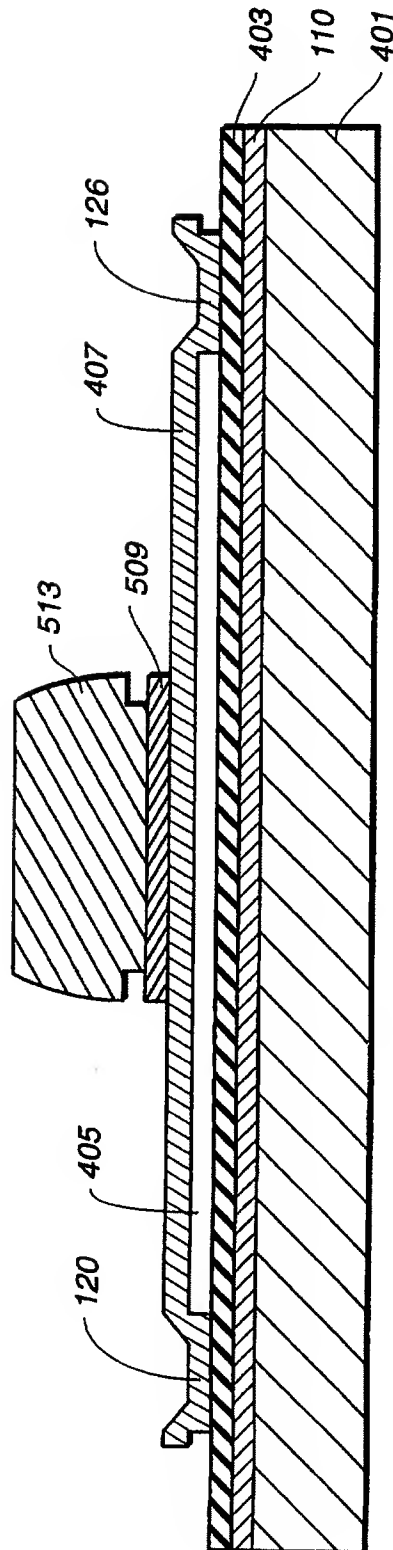


FIG. 7E

## INTERNATIONAL SEARCH REPORT

International application No.

PCT/US97/08087

**A. CLASSIFICATION OF SUBJECT MATTER**

IPC(6) : HO1L 29/82; HO1H 51/22

US CL : 257/415, 422, 686, 689; 335/78, 80; 361/819

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 257/415, 422, 686, 689; 335/78, 80; 361/819

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5,398,011 A (KIMURA ET AL.) 14 March 1995, See entire document.	1-11
Y	US 5,557,132 A (TAKAHASHI) 17 September 1996, See entire document.	1-11

☐ Further documents are listed in the continuation of Box C.☐ See patent family annex.

* Special categories of cited documents:	*T	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
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*E* earlier document published on or after the international filing date	*Y*	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
*L* document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	*Z*	document member of the same patent family
*O* document referring to an oral disclosure, use, exhibition or other means		
*P* document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search

13 JULY 1997

Date of mailing of the international search report

20 AUG 1997

Name and mailing address of the ISA/US  
Commissioner of Patents and Trademarks  
Box PCT  
Washington, D.C. 20231

Facsimile No. (703) 305-3230

Authorized officer

LINCOLN DINOYAN

Telephone No. (703) 308-3111